A Field Study of Footprint-Scale Variability of Raindrop Size Distribution

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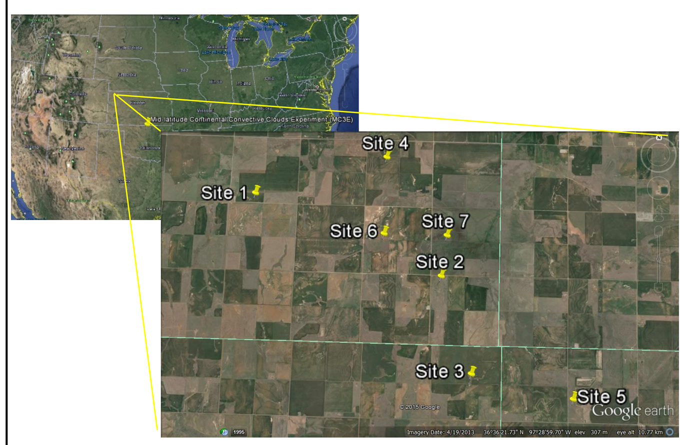
1. Introduction

The retrieval of raindrop size distribution (DSD) from dual frequency precipitation radar (DPR) on board GPM core satellite is one of the key objectives of the NASA's Global Precipitation Measurement (GPM) mission. The footprint of the DPR is nearly circular at approximately 5 km diameter and the non-uniform beam filling (NUBF) within the footprint is one of the uncertainties of the retrieved size distribution. The NUBF occurs in both horizontal and vertical dimension and results from the combination of the gradient of rain intensity and partial filling within the footprint. The embedded convection and the squall lines with trailing stratiform rain are frequently observed during frontal passage and result in sharp gradients in rain intensity within a few kilometers. The air mass thunderstorms and patchy stratiform rain in the presence of dry layer near the Earth's surface results in gaps in the DPR footprint. This study investigates the horizontal spatial variability of DSD due to the gradient of rain intensity within DPR footprint. The footprint-scale variability of DSD was studied through disdrometer measurements collected during Mid-latitude Continental Convective Clouds Experiment (MC3E). The findings of this study were compared to a similar study conducted using the disdrometer dataset from the NASA Wallops Flight Facility (WFF).

2. Sites and Instrumentation

The MC3E campaign was conducted in North Central Oklahoma (36.7N, 97.1W) from April 22 through June 6, 2011. Seven third-generation compact two-dimensional video disdrometers (2DVD) were deployed at and around the ARM SGP site where the distances between the units ranged from 0.4 to 9.2 km. The 2DVDs are delicate and failed to operate continuously throughout the experiment. The drop-by-drop raw outputs are generated on a daily basis and it is hard to pinpoint the time of its failure. In that regard, this study focused on the dataset when all units reported rainfall. The comparative 2DVD dataset at WFF consisted of wintertime stratiform rainfall, while continental convective storms dominated the MC3E. The WFF experiment included six 2DVDs where the minimum and maximum separation distances were 0.5 and 2.3 km, respectively.



	Site #	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
	Location	36.623°N, 97.532°W	36.618°N, 97.479°W	36.581°N, 97.479°W	36.632°N, 97.481°W	36.578°N, 97.445°W	36.606°N, 97.488°W	36.604°N, 97.485°W
Site 1			4.75	6.67	4.65	9.24	4.37	4.70
Site 2		4.75		4.14	1.58	5.40	1.53	1.65
Site 3		6.67	4.14		5.72	3.03	2.93	2.63
Site 4		4.65	1.58	5.72		6.84	2.95	3.16
Site 5		9.24	5.40	3.03	6.84		4.94	4.59
Site 6		4.37	1.53	2.93	2.95	4.94		0.36
Site 7		4.70	1.65	2.63	3.16	4.59	0.36	

The figures on the left show the MC3E field measurement and the arrangement of measuring sites where a 2DVD was installed. The table reports the coordinates of the sites with the relative distances.

3. Data Analysis and Methodology

Three different rain/no-rain thresholds are then applied to the one-minute observations. All thresholds use minimum of 10 drops. The minimum RR of 0.1 mm h^{-1} resulted in 592 one-minute sample when all seven 2DVD at MC3E reported rainfall. Considering the minimum detectable reflectivity of GPM DPR, the Ku-band reflectivity (Z_{Ku}) of 18 dBZ and Ka-band reflectivity (Z_{Ka}) of 12 dBZ are the other two thresholds used in this study., resulting in 396 and 589 one-minute samples, respectively. The same thresholds are used for the WFF data. The sample size resulted different, and of 447, 445 and 278 for RR, Z_{ku} and Z_{ka}, respectively.

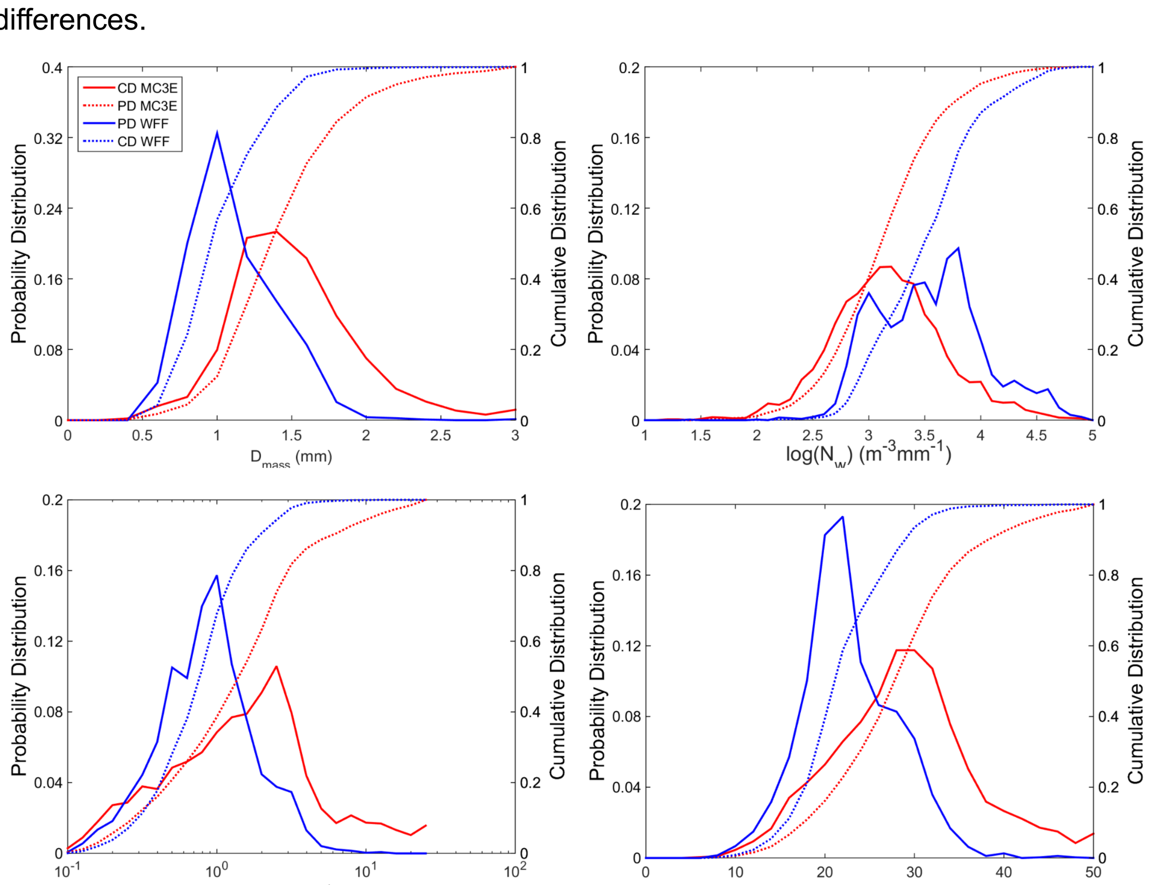
A three-parameter exponential function was used to investigate the spatial variability of fifteen DSD parameters. The exponential function is expressed as:

$$r(d) = r_0 \exp\left(-\frac{d}{d_0}\right)^{s_0}$$

where r_0, s_0 are nugget and shape parameters and d_0 is the correlation distance. The correlation, r, between the paired 2DVD observations at distance, d, is calculated from Pearson correlation coefficient. There were 21 and 15 paired 2DVD observations in MC3E and WFF, respectively. The r_0 is the correlation between the collocated observations and is set to 0.99, 0.95 and 0.90. Following an initial guess of d_0 and s_0 between the range of 0 to 300 at 0.1 increment and 0 to 2 at 0.01 increment, respectively, the d_0 and s_0 are calculated minimizing the root-mean square error (RMSE) between the observation and equation based correlations. The RMSE is the measure of the goodness of the fit and it is critical for the interpretation of d_0 and s_0 .

4. Probability and Cumulative Distribution

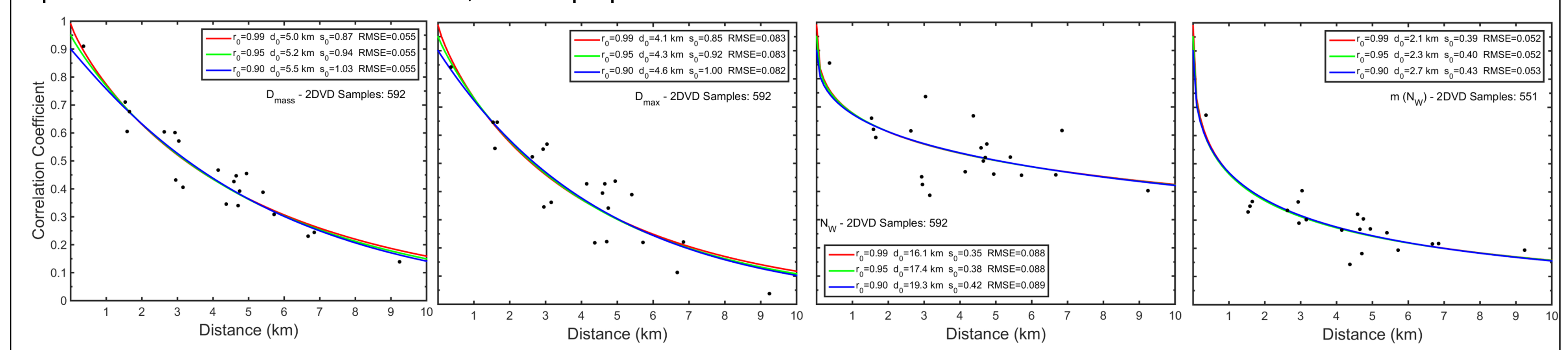
The Probability Distribution (PD) of the Cumulative Distributions (CD) of the DSD and rain parameters provide an insight on the characteristics of DSD and rainfall. The PD and CD derived from MC3E and WFF observations exhibited significant differences.



The mass weighted diameter (D_{mass}), had higher values during MC3E (mode 1.4 mm) than during WFF (mode 1.0 mm). The PD of logarithmic normalized intercept parameter with respect to the liquid water content $\log(N_w)$ had a single peak at around 3.2 $m^{-3}mm^{-1}$ during MC3E, while had multi peak distribution with mode at 3.8 $m^{-3}mm^{-1}$ during WFF. The PD of RR was unimodal in both MC3E and WFF but there were drastic shift between the distributions, with modes of 2.51 and 1.00 mmh^{-1}, respectively. A wide distribution of PD of Z_{ku} was evident during MC3E where peak was around 29 dBZ. A relatively narrow distribution with peak at 21 dBZ was observed during WFF.

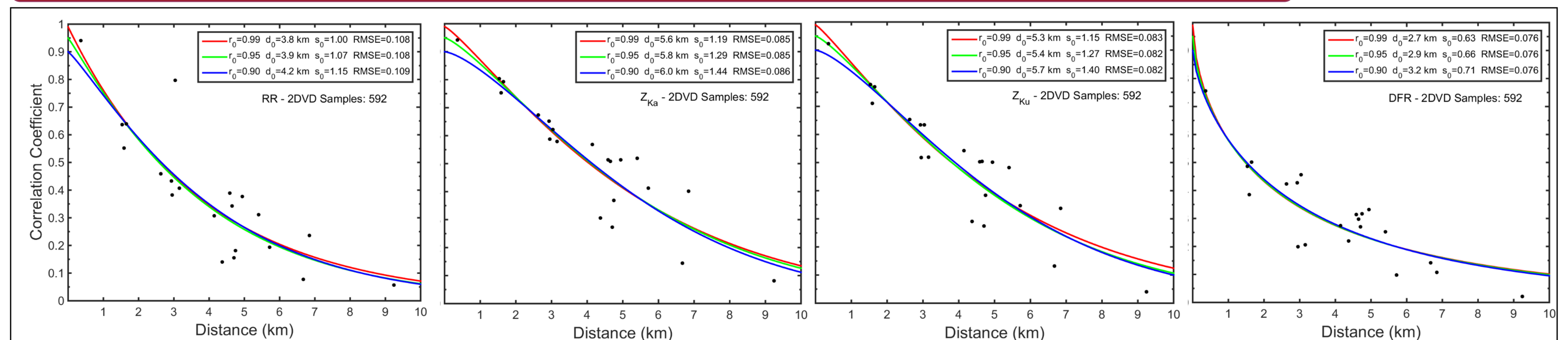
5. Small scale variability analysis – DSD parameters (RR threshold)

The figures below, as well those of Section 6, show the three-parameter exponential function estimated for three different values of r_0 for MC3E. The points represent the calculated correlation coefficient for each disdrometer pair. In the legend are reported also the correlation distance, the shape parameter and the RMSE.



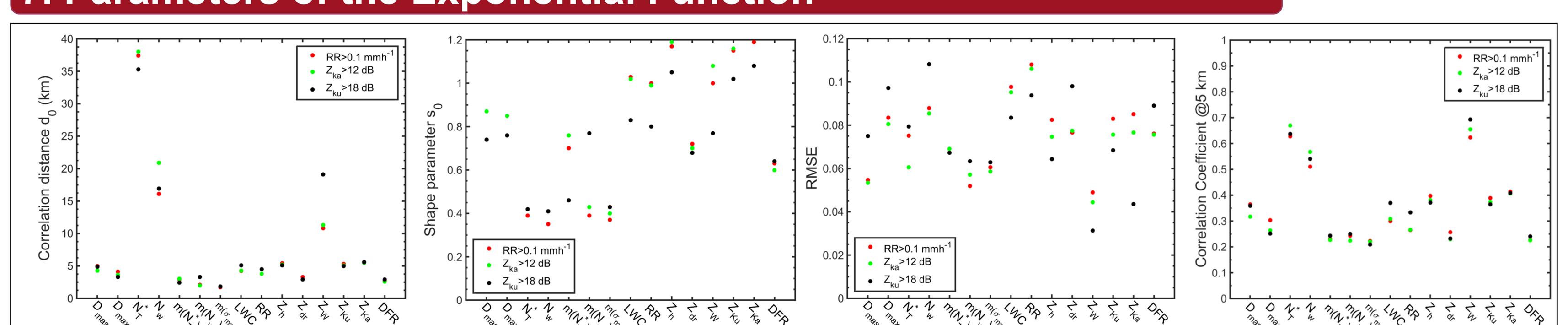
The correlations of D_{mass} decreased slightly lower than those of D_{max} at all distances. At a given distance, the maximum differences in correlations were 0.15 in D_{mass} and 0.20 in D_{max}. The less spread in correlations results in lower RMSE, which indicates better fit of the exponential function. The decrease in correlations of N_W was more gradual than D_{mass} or D_{mass} with distance. The spread in correlations was 0.4 at 3 km but 0.1 or less at other distances. The shape parameter of gamma distribution with respect to N_W, m(N_W), had correlations of 0.4 or lower at distances longer than 1.5 km but the decrease was gradual in these distances. The spread in correlations of m(N_W) was as 0.2 or less. The fitted exponential function was marginally sensitive to the differences in r_0. D_{mass} and D_{max} have correlation distance comparable with the DPR footprint, while larger and lower values are obtained for N_w and m(N_w), respectively.

6. Small scale variability analysis – Rain parameters (RR threshold)



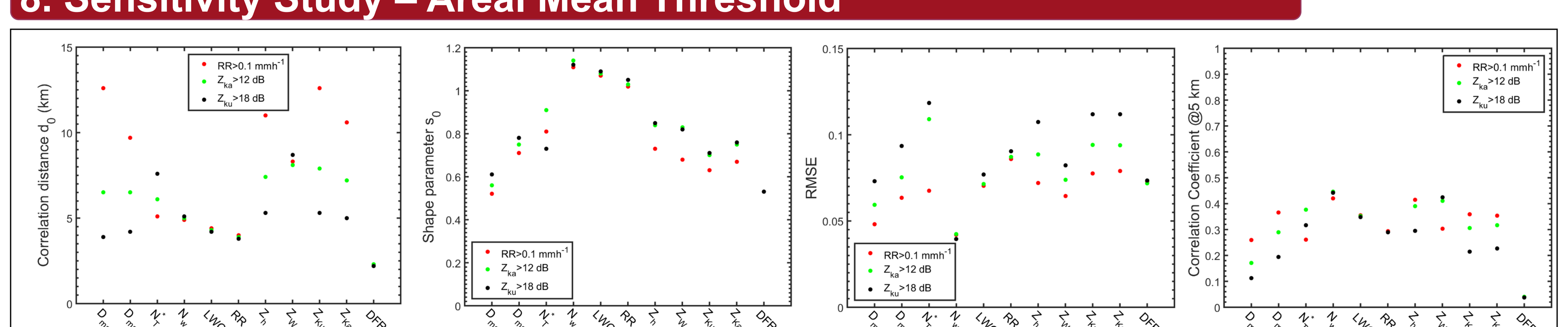
The correlations of RR, Z_{Ka}, and Z_{Ku} decreased with distance from around 0.95 at the shortest distance to less than 0.1 at the farthest distance. This sharp decrease in correlations was attributed to the convective nature of the precipitation during MC3E. The RR had relatively sharper decrease than the Z_{Ka}, and Z_{Ku} where the correlation of 0.5 was observed at 3 km in RR and 4 km in Z_{Ka}, and Z_{Ku}. The spread in correlations of RR was 0.25 or less except one outlier at 3 km. This outlier resulted in relatively high RMSE (> 0.1). The correlations had a spread of 0.25 or less at a distance in Z_{Ka}, and Z_{Ku} resulting in RMSE of 0.08. The dual frequency ratio (DFR) had the sharpest decrease among other rain parameters reaching correlation of 0.5 at 1.5 km but the decrease in correlations was gradual at longer distances. The correlation distance of RR and reflectivity at Ka and Ku band is very close to the diameter of the DPR footprint, while DFR has lower values.

7. Parameters of the Exponential Function



The parameters of exponential function, d_0 and s_0, had mostly insensitive to the choice of rain/no-rain threshold for most of the physical parameters. The d_0 was mostly 5 km or less for most of the physical parameter, which indicates the highly variable nature of convective rainfall. The d_0 was between 2-3 km for shape parameters of gamma distribution (m) for all three methods. The reflectivity at S-, K_u-, and K_a-band had d_0 of 5-6 km, while N_T^* and N_W, had the highest d_0 values. The s_0 reflected the variation of the correlation with distance. For m values, the s_0 was around 0.4, while the s_0 of 1.15 was observed for Z_h, Z_{Ka}, and Z_{Ku}. The RMSE remained less than 0.11 for all physical parameters justifying the success of the exponential fit. The correlation coefficient calculated at 5 km (footprint diameter), from fitted exponential function at r_0 of 0.99 for all physical parameters, quantifying the spatial variability within DPR footprint. The correlations of m values were 0.25, while correlations of Z_h, Z_{Ka}, and Z_{Ku} were 0.4. The correlation of RR was 0.3, while the correlations of D_{mass} and D_{max} were 0.35 and 0.3, respectively. These low correlations are again the evidence of highly variable nature of convective rainfall, but indicate also an e-folding decay within a DPR footprint.

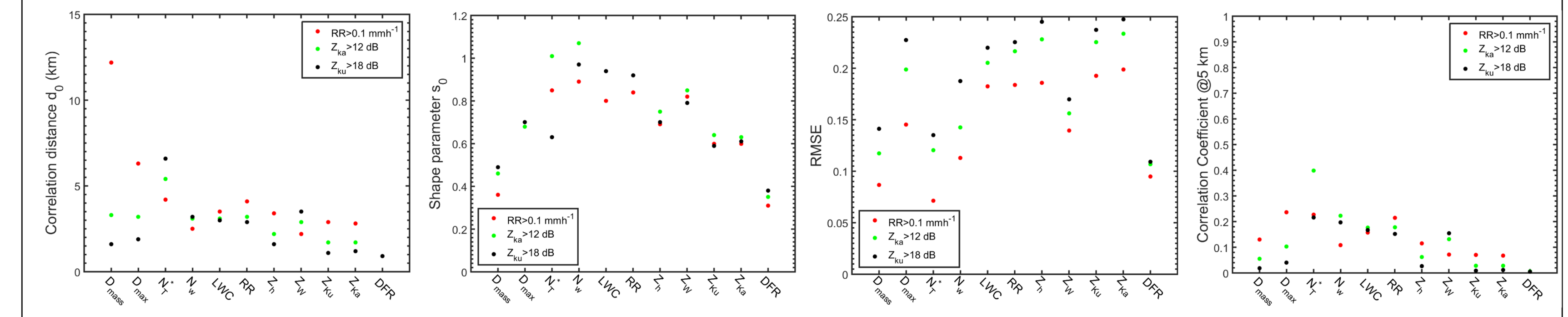
8. Sensitivity Study – Areal Mean Threshold



The rain/no-rain threshold was also applied to the areal mean RR, Z_{Ka}, and Z_{Ku}. The areal mean threshold sample sizes were 38 to 70% more than the individual observation based threshold sample sizes. Both D_{mass} and D_{max} and the reflectivity at S-, Ka- and Ku-band show a marked sensitivity to the choice of rain/no-rain threshold. The shape parameter s_0 ranges between 0.5 and 1.2, while the RMSE is lower than 0.12. The correlation coefficient at DPR footprint diameter is around 0.4 reaching the maximum of 0.5 for N_W; very low value, close to zero, is obtained for DFR.

9. Sensitivity Study – Rain Intermittence

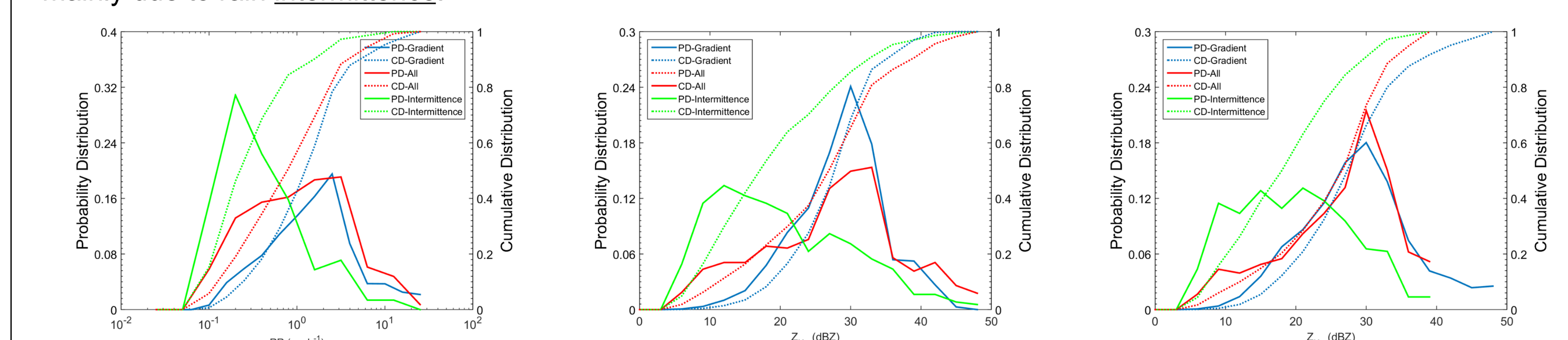
Rain intermittence within the instantaneous field of view of microwave sensor or footprint of DPR is one of the sources of the Non-Uniform Beam Filling (NUBF) and is one of key uncertainties in precipitation estimates. Following a clear distinction between no-rain and no-data in 2DVD dataset, the spatial variability of DSD and rainfall parameters was reanalyzed when one or more disdrometers reported rainfall below the minimum rain/no-rain threshold. The areal mean threshold was kept above the rain threshold. The sample size was 62 % to 75% lower than the sample size in section 8, as function of the rain/no-rain threshold considered.



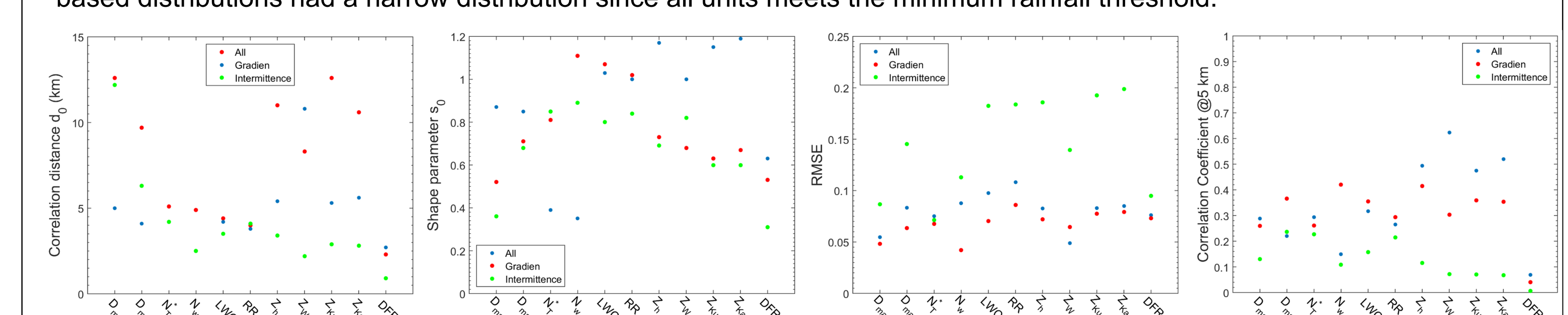
The RMSE was relatively high due to the limited sample size. The d0 was mostly less than 5 km and was not sensitive to the choice of rain threshold for rainfall parameters. The d0 of DSD parameters, on the other hand, was sensitive to the choice of rain threshold. The d_0 of D_{mass} and D_{max}, for instance, was noticeably higher for RR based threshold than Z_{Ku} and Z_{Ka} based thresholds. The s_0 has generally low values, ranging from 0.3 to 1.1 according to the short correlation distances. This is reflected by very low values of correlation coefficient at 5 km (DPR footprint diameter). The RMSE is high, always over 0.1 except two cases (D_{mass} and NT*) with most of the values around 0.2. The low correlation distances of the most of the parameters together with high RMSE, evidence the higher variability of the precipitation in NUBF cases.

10. Comparison of Datasets (Gradient, Intermittence, All)

This study used three different datasets of 2DVD observations. First, all seven units reported rainfall above the minimum rainfall threshold. The spatial variability under this condition was resulted from gradient in rain intensity across the sampling area. Second, the areal mean rainfall was above the minimum rainfall threshold. This enhanced the sample size since there was no requirement for the individual units to be above the rainfall threshold. The spatial variability was then resulted from gradient + intermittence (= all). Third, the subsample of the second dataset was considered. This limited sample included the observations when one or more units were below the minimum rainfall threshold. This spatial variability was mainly due to rain intermittence.

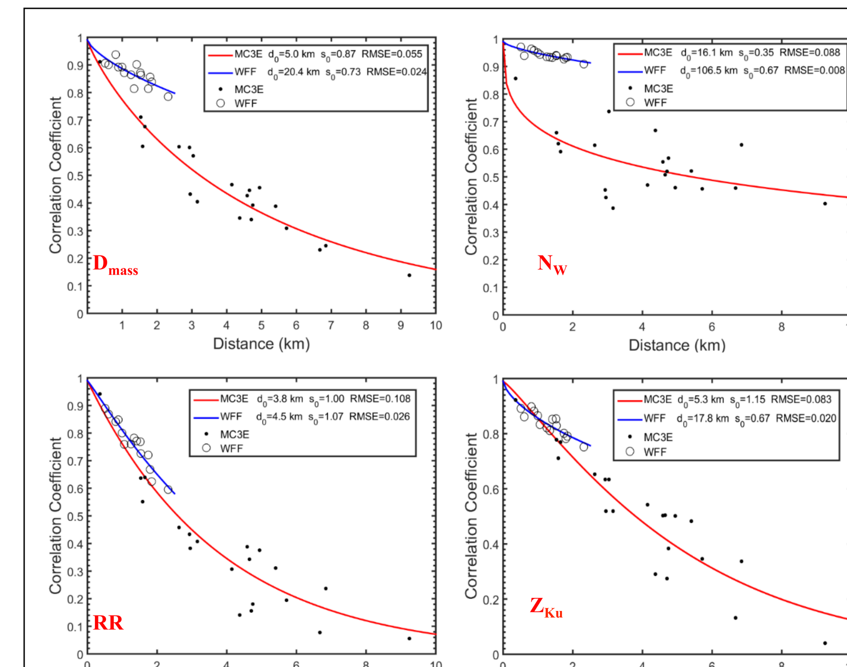


The probability and cumulative distributions were constructed by combining all 2DVD records. In the presence of *intermittence*, the distributions were shifted toward lighter rain and lower Z_{Ka} and Z_{Ku}. The distributions of *all* is expected to be broader since it has the highest sample where the individual units could have light and very heavy rain. The *gradient* based distributions had a narrow distribution since all units meets the minimum rainfall threshold.



There were noticeable differences in d_0 of D_{mass} and D_{max} as well as d_0 of reflectivities between the three datasets. The d_0 of LWC, RR, and DFR was less sensitive to the choice of datasets. The s_0 varied between 0.4 and 1.2. For all and gradient datasets, the s_0 was unity for RR. Since r_0 and d_0 are 0.99 and 4 km, respectively, the correlation becomes 0.99 exp(-d/4). At 5 km, correlation is 0.3. This shows the high spatial variability due to convective characteristics of MC3E dataset. The RMSE was relatively high for intermittence datasets. The correlations were relatively low for intermittence dataset for most of the parameters. This shows that intermittence results in higher spatial variability than gradient. The all dataset which represents more realistic nature of precipitation had correlations between 0.3 and 0.4 at 5 km.

11. Comparison of Datasets (MC3E vs WFF)



The footprint-scale variability of DSD in MC3E is the follow up study of the pixel-scale variability of DSD in WFF. The differences in correlations of the physical parameters between the two experiments were resulted from the differences in characteristics of DSD and rainfall as shown in PD and CD. The correlations were higher in WFF than in MC3E at a given distance resulting higher d_0 in WFF. The exponential fit and also the calculated correlations of the two sites, are generally closer to each other for rain parameters with respect DSD parameters. It should be noted that the maximum separation distance is the key to evaluate the spatial variability within the study domain. While the longer separation distances are desirable to investigate the spatial variability for larger field of view of microwave sensors, there is also a need to have more instruments so the exponential distribution quantifies the variability more accurately.

Acknowledgments

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